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Annual Technical Report

on

AEOSR-TR- 92 0450

TURBULENT REACTING FLOWS AND SUPERSONIC COMBUSTION

Grant AFOSR-90-0151

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

For the Period

15 February 1991 to 14 February 1992

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Stanford University 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR/NA
6c. ADDRESS (City, State, and ZIP Code) Department of Mechanical Engineering Stanford, CA 94305	7b. ADDRESS (City, State, and ZIP Code) Building 410, Bolling AFB DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR/NA 8b. OFFICE SYMBOL (If applicable) NA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-90-0151
8c. ADDRESS (City, State, and ZIP Code) Building 410, Bolling AFB DC 20332-6448	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61103D	3484	A1	

11. TITLE (Include Security Classification)

(U) Turbulent Reacting Flows and Supersonic Combustion

12. PERSONAL AUTHOR(S) C. T. Bowman, R. K. Hanson, M. G. Mungal and W. C. Reynolds

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Annual Technical Report	FROM 15-2-91 TO 14-2-92	1992, March 15	27

16. SUPPLEMENTARY NOTATION

—

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	turbulent reacting flow, supersonic combustion

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

An experimental and computational investigation of supersonic non-reacting and combustion flows is in progress. The principal objective of the research is to gain a more fundamental understanding of mixing and chemical reaction in supersonic flows. The research effort comprises three inter-related elements: (1) an experimental study of mixing and combustion in a supersonic plane mixing layer; (2) development of laser-induced fluorescence techniques for time-resolved two-dimensional imaging of species concentration, temperature, velocity and pressure; and, (3) numerical simulations of compressible reacting flows. The specific objectives and the status of the research of each of these program elements are summarized in this report.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Julian M Tishkoff	22b. TELEPHONE (Include Area Code) (202) 767-4935	22c. OFFICE SYMBOL AFOSR/NA

DD Form 1473, JUN 86 *Previous editions are obsolete.* SECURITY CLASSIFICATION OF THIS PAGE

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1.0 SUMMARY

An experimental and computational investigation of supersonic combustion flows is in progress. The principal objective of the research is to gain a more fundamental understanding of mixing and chemical reaction in supersonic flows. The research effort comprises three inter-related elements: (1) an experimental study of mixing and combustion in a supersonic plane mixing layer; (2) development of laser-induced fluorescence techniques for time-resolved two-dimensional imaging of species concentration, temperature, velocity and pressure; and, (3) numerical simulations of compressible reacting flows. The specific objectives and the status of the research of each of these program elements is summarized in this report.

2.0 INTRODUCTION

Air-breathing propulsion systems offer the potential of higher performance than conventional rocket engines for hypersonic flight. To realize this potential, new combustor design concepts are required. In particular, in order to minimize losses associated with strong shock waves and high combustor inlet temperatures, it is desirable to maintain high flow velocities in the combustion chamber. This design concept leads to a new class of propulsion devices where combustion takes place in supersonic flow.

Combustion in supersonic flow is fundamentally different from combustion in the subsonic flow regime employed in all currently operating aircraft engines. Many of the design approaches developed over the years for subsonic combustors, e.g. ignition and flame stabilization techniques, are not applicable to supersonic combustion devices, and the current understanding of the fundamental aspects of supersonic combustion is inadequate to support the development of these devices.

Recent advances in diagnostic capabilities and significant improvements in our ability to compute such flows offer new opportunities to obtain the needed fundamental understanding of compressible turbulent reacting flows. To achieve this understanding, a closely coordinated experimental and computational program which utilizes state-of-the-art experimental techniques and computational methods is needed. We are engaged in such an effort with support from the Air Force Office of Scientific Research.

The principal objective of the research is to gain a more fundamental understanding of the flow physics and chemistry interactions in compressible turbulent reacting flows. The project comprises three interrelated efforts: (1) an experimental study of mixing and combustion in supersonic flows, (2) development of laser-induced fluorescence techniques for time-resolved multi-dimensional imaging of species concentration, temperature, velocity and pressure in supersonic flows, and (3) simulation and modeling of supersonic flows with mixing and chemical reaction. A close coupling among these efforts is maintained in order to maximize our understanding of supersonic turbulent reacting flows, with emphasis on supersonic combustion. The specific objectives and status of the research of each of the program elements is described below.

3.0 MIXING AND REACTION IN SUPERSONIC FLOW

3.1 Objectives

The objective of this part of the program is the experimental study of mixing and chemical reaction in a compressible mixing layer. Data acquired using conventional and laser-based diagnostics provide important new knowledge about mixing and reaction under compressible conditions.

3.2 Status of the Research

Figure 1 shows a schematic of the flow facility used in the experimental investigation of supersonic mixing and combustion flows. This facility is described in detail in Clemens and Mungal (1990). Different convective Mach numbers, M_c, are achieved by varying the inlet Mach numbers and stagnation temperatures. In the reacting flow studies, the high-speed stream (stream 1) is hot, vitiated air and the low-speed stream (stream 2) is a mixture of hydrogen and nitrogen. High-speed stream stagnation temperatures between 1400 and 2000 K are produced burning hydrogen and air in a vitiation air heater upstream of the nozzle plenum. By adding oxygen to the combustion products, the oxygen mol fraction in the high-speed stream may be varied from 2 to 21 percent. The hydrogen mol fraction in the low-speed stream may be varied from zero (non-reacting) to 20 percent, thereby allowing a significant variation in the heat release.

In our investigation of mixing and reaction in supersonic flow, our strategy is first to investigate mixing phenomena in non-reacting flows and then to investigate reacting flows. Significant experimental findings obtained during the past year are summarized below.

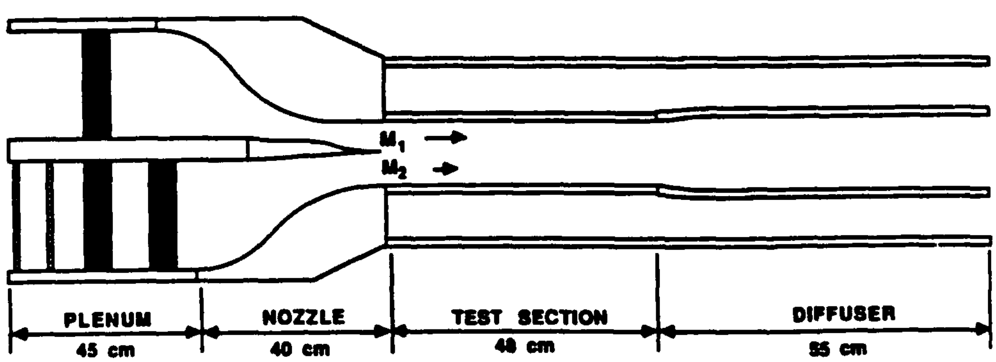


Fig. 1. Schematic diagram of the supersonic flow facility.

3.2.1 Summary of Mixing Studies

A detailed description of results from our previous mixing studies were contained in last year's Annual Technical Report. A complete report is contained in the Ph.D. thesis of N. T. Clemens (1991). Here, we summarize the main findings:

- A simple Planar Laser Mie Scattering (PLMS) visualization technique was developed as an alternative to spatially-integrating schlieren techniques. The PLMS technique allows easy visualizations of mixed fluid in the shear layer for several views, typically the side, plan and end-views (see Clemens & Mungal, 1991).

- Using the PLMS technique, it was shown that the layer changes from a predominantly Brown-Roshko roller-like structure at low compressibility, to a structure which is more three-dimensional at moderate and high compressibility. It also was shown that this change in structure is a compressibility effect and not a Reynolds number effect (see Clemens & Mungal, 1992a).

- Planar Laser Induced Fluorescence (PLIF) of nitric oxide confirmed the structural changes found using the PLMS technique and quantified changes in mixing. Here, it was found that at low compressibility, the mixture fraction of the Brown-Roshko rollers tends to be uniform in the cross-stream direction and ramped in the streamwise direction. At higher compressibility, however, it was found that the layer often consists of at least two values of mixture fraction in the cross-stream direction together with ramps in the streamwise direction. In addition, while the growth rate of the layer decreases with increasing compressibility, the efficiency of mixing within the layer is observed to increase (see Clemens et al., 1991).

- Side-wall disturbance generators located within the supersonic nozzles were shown to be quite effective in producing large distortions of the mixing layer that might result in mixing enhancement. Since this approach uses the wave system inherent in supersonic flow, there is no analog to this technique in subsonic flow (see Clemens & Mungal, 1992b).

3.2.2 Reacting Flow Studies

Following completion of the mixing studies, summarized in Section 3.2.1, the supersonic flow facility was configured for reacting flow experiments. The significant modifications of the flow facility included: (a) addition of a hydrogen-nitrogen diluent flow system for the low-speed stream, (b) addition of a make-up oxygen system for the high-speed vitiated air stream, (c) fabrication of a new splitter tip for the convective Mach number range of the reacting flow experiments, (d) addition of water sprays in the exhaust system for cooling and quenching the hot exhaust gases, (e) upgrading the computer control system to handle the additional control variables required for reacting flow experiments and to allow remote operation, (f) fabrication of quartz test section windows, and (g) addition of flame detectors at strategic locations within the test section, diffuser and exhaust system.

Initial tests were conducted in which the vitiation air heater was operated over a range of conditions to verify the performance of the heater and to confirm that the thermal protection of critical parts of the facility was adequate for the planned high temperatures. These test verified satisfactory performance of the air heater for stagnation temperatures from 600 to 2000 K and showed that no additional modifications of the facility were required for high-temperature operation.

Following the vitiation air heater tests, a series of experiments was conducted in non-reacting flows with high-speed stagnation temperatures in the range 1200 to 1900 K. The objective of these tests was to establish the growth rate of the compressible non-reacting mixing layer for variable densities. The high-speed convective Mach number in these experiments was in the range 0.8 to 0.9, and the low-speed to high-speed density ratio varied from 4 - 6. A typical spark Schlieren image of the non-reacting variable density mixing layer is shown in Fig. 2. The growth rate of the mixing layer, based on these Schlieren images, was consistent with previously-reported correlations for compressible mixing layers (Papamoschou, 1991).

The objective of the first reacting flow experiments was to establish the ignition envelope for the mixing layer. In these experiments, three primary parameters were varied: (a) high-speed stream stagnation temperature, (b) high-speed stream oxygen mol fraction, and (c) low-speed stream hydrogen mol fraction. Because of safety concerns, the range of these parameters was restricted so as to preclude having a flammable mixture in the exhaust system at any time. This constraint limited hydrogen mol fractions in the low-speed stream to less than 10 percent.

Ignition in the mixing layer was verified by means of photographic images of OH emission. A typical set of OH emission images is shown in Fig. 3. Here, the high-speed stream stagnation temperature is 1900 K; the high-speed stream Mach number is 1.35 and the oxygen mol fraction is 16 percent. The low-speed stream Mach number is 0.3 and the hydrogen mol fraction is 6 percent. The high-speed convective Mach number is 0.88. It is seen that ignition occurs immediately downstream of the splitter tip and that reaction continues throughout the test section. The faint OH emission in the high-speed vitiated air stream, observed at the furthest upstream station, is residual emission from combustion

Fig. 2. Schlieren image of nonreacting mixing layer. Top stream: T_0 = 1900 K and M = 1.35; bottom stream: T_0 = 300 K and M = 0.3. M_c = 0.88 and P_{static} = 12 psi. Splitter tip is located at the left-hand side of the image.

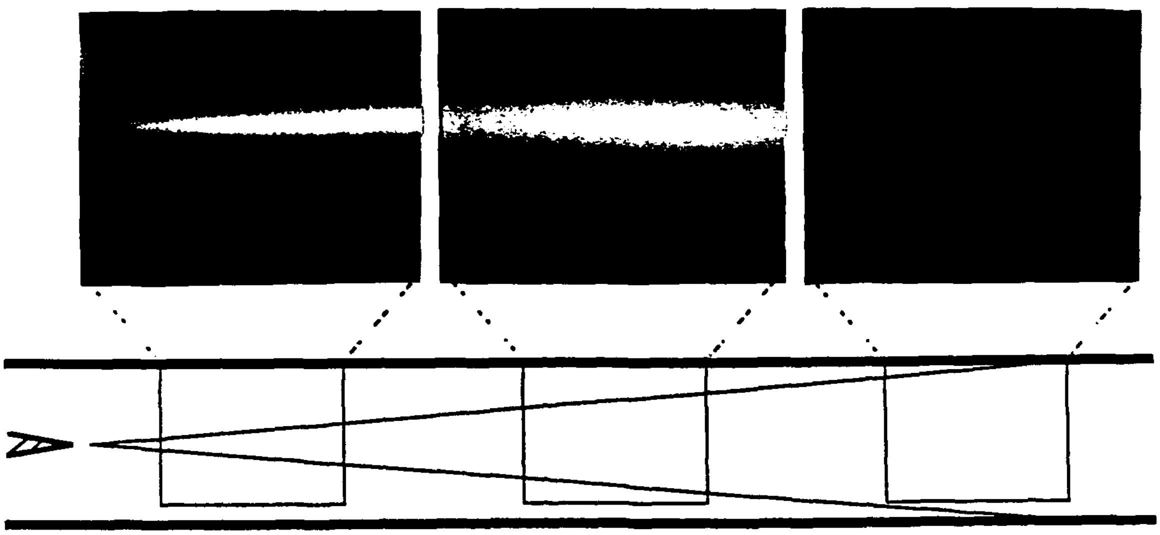


Fig. 3. Composite ultraviolet emission image of reacting mixing layer. Top stream: T_0 = 1900 K, M = 1.35 and X_{O2} = 0.16; bottom stream: T_0 = 300 K, M = 0.3 and X_{H2} = 0.06. M_c = 0.88 and P_{static} = 12 psi.

products of the vitiation air heater. A typical ignition envelope is shown in Fig. 4. These data show that a range of hydrogen mol fractions are accessible for combustion tests, which meets our exhaust system flammability criterion. All initial reacting flow experiments will be conducted within this ignition envelope.

Preliminary comparisons of OH emission images with spark schlieren images of the reacting mixing layer indicate that the region of intense chemical reaction is located very near the high-speed boundary of the mixing layer. Further experiments are planned to examine the location of the reaction zone.

3.3 Future Work

During the next year, we plan to continue the reacting flow experiments. In particular, experiments will be conducted to investigate:

- The effect of heat release on the growth rate and structure of the compressible reacting mixing layer.
- The dependence of ignition location (flame standoff distance) on high-speed stream static temperature, convective Mach number, and freestream oxygen and hydrogen mol fractions.
- The effects of Damköhler number for compressible reacting mixing layers.

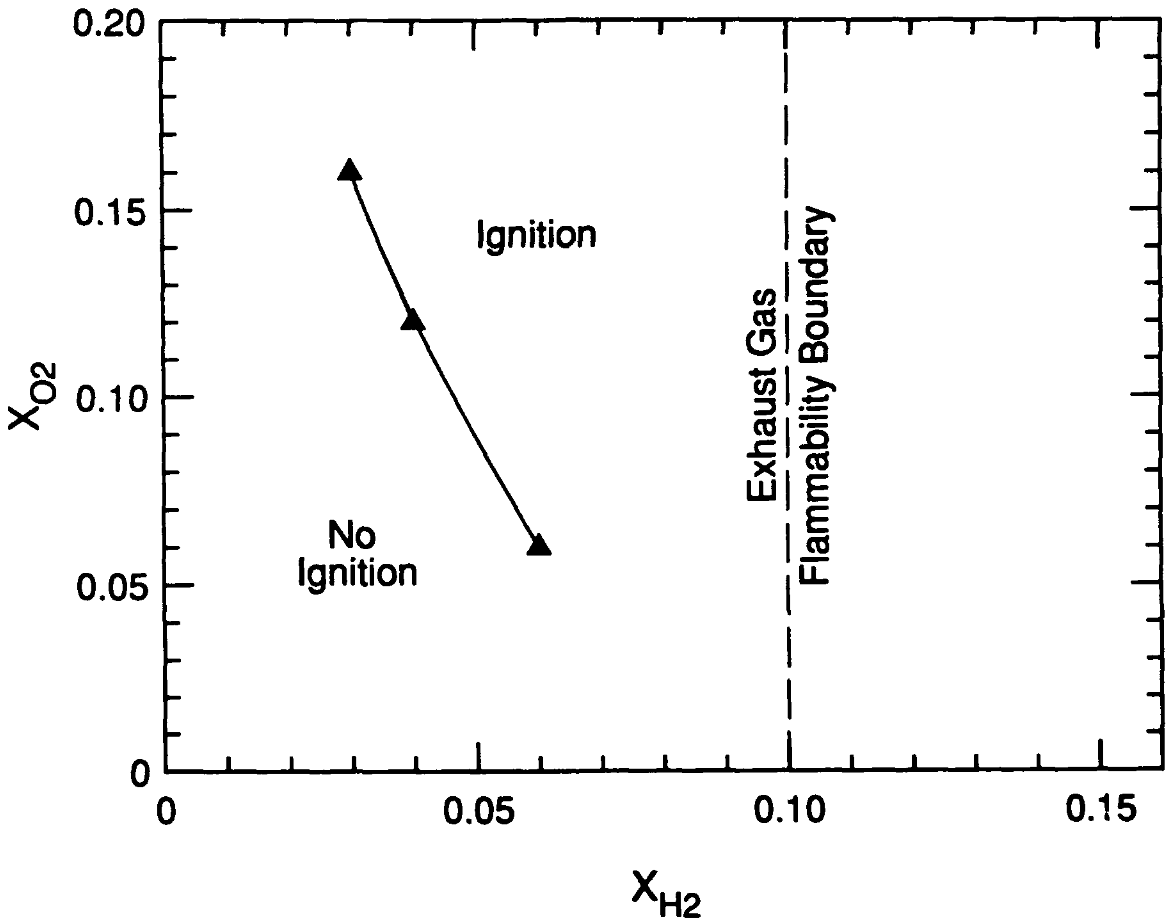


Fig. 4. **Ignition boundary of reacting mixing layer. T_0 = 1900 K and M = 1.35; bottom stream: T_0 = 300 K and M = 0.3. M_c = 0.88 and P_{static} = 12 psi. Exhaust gas flammability boundary indicates maximum hydrogen mol fraction in fuel stream for nonflammable exhaust gas mixtures.**

4.0 SUPERSONIC FLOW DIAGNOSTICS

4.1 Objectives

This element of our research program is aimed at developing flowfield imaging diagnostics based on Planar Laser-Induced Fluorescence (PLIF). Flow parameters of interest include species concentrations (or mol fractions), temperature, velocity and pressure. Particular emphasis is placed on imaging nitric oxide (NO), molecular oxygen (O_2) and hydroxyl radical (OH), since these species are naturally present in most supersonic propulsion flows of interest, including the Stanford supersonic mixing layer facility.

4.2 Status of the Research

Work over this reporting period has been in three areas: (1) code development for method-of-characteristics solutions of nonequilibrium supersonic free jets; (2) PLIF imaging of hypersonic shock tunnel flow; and (3) PLIF imaging of mixing and combustion of transverse jets in shock-generated supersonic flow.

4.2.1 Flowfield Code Development

During the past three years we have been working to assemble a computer code based on the method-of-characteristics (MOC) to describe nonequilibrium supersonic free jets. This flow is ideal for diagnostics research on high-speed flows owing to the extremely wide range of flow conditions which can be accurately generated. The MOC code is now operational and in use to evaluate PLIF imaging data acquired in our shock tunnel (discussed in Sec. 4.2.2). At the present time, the code is able to handle three critical flowfield cases: (1) constant gamma (ratio of specific heats); (2) vibrationally equilibrated flow (infinite relaxation rate); and (3) finite relaxation rate. In each case, the code calculates the entire flow between the nozzle exit (sonic conditions) and the Mach disc; see Fig. 5 for a schematic of the flowfield. An example result showing the variation of temperature along the jet centerline is shown in Fig. 6. In this case, the flow is a 2/77/21 mixture of $NO/N_2/O_2$, but several different mixtures involving various proportions of these gases are under study. Results are indicated for both the vibrational and translational/rotational temperatures of NO and O_2 and for a range of vibrational relaxation rates. The rates for V-T relaxation of NO by NO and for V-V transfer between NO and O_2 are especially critical; these control the separate "freezing" of the vibrational temperatures of the NO and O_2, for example. The coupling between the jet gasdynamics and the nonequilibrium processes is clear from this figure.

In the future, we will explore extension of the MOC code to include chemical nonequilibrium.

Underexpanded Supersonic Free Jet Flowfield

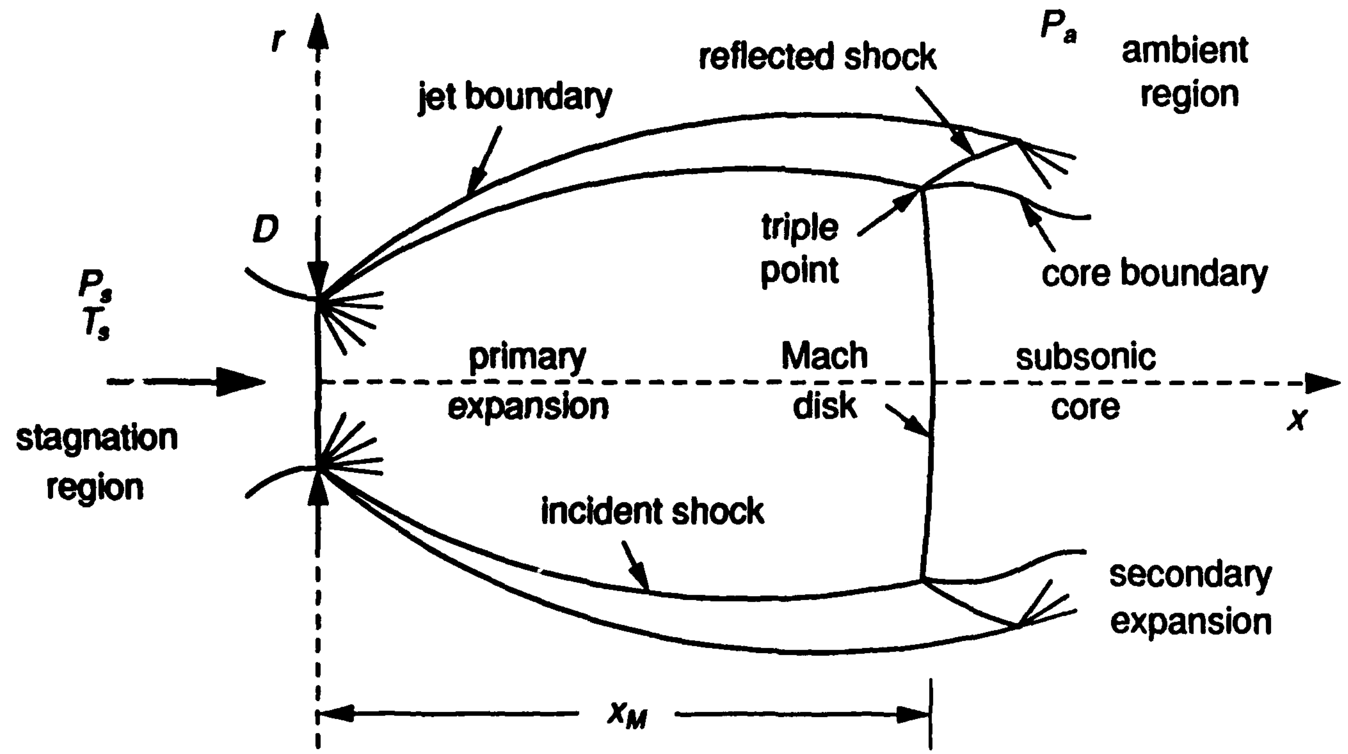


Fig. 5. Schematic of underexpanded, supersonic free jet flowfield.

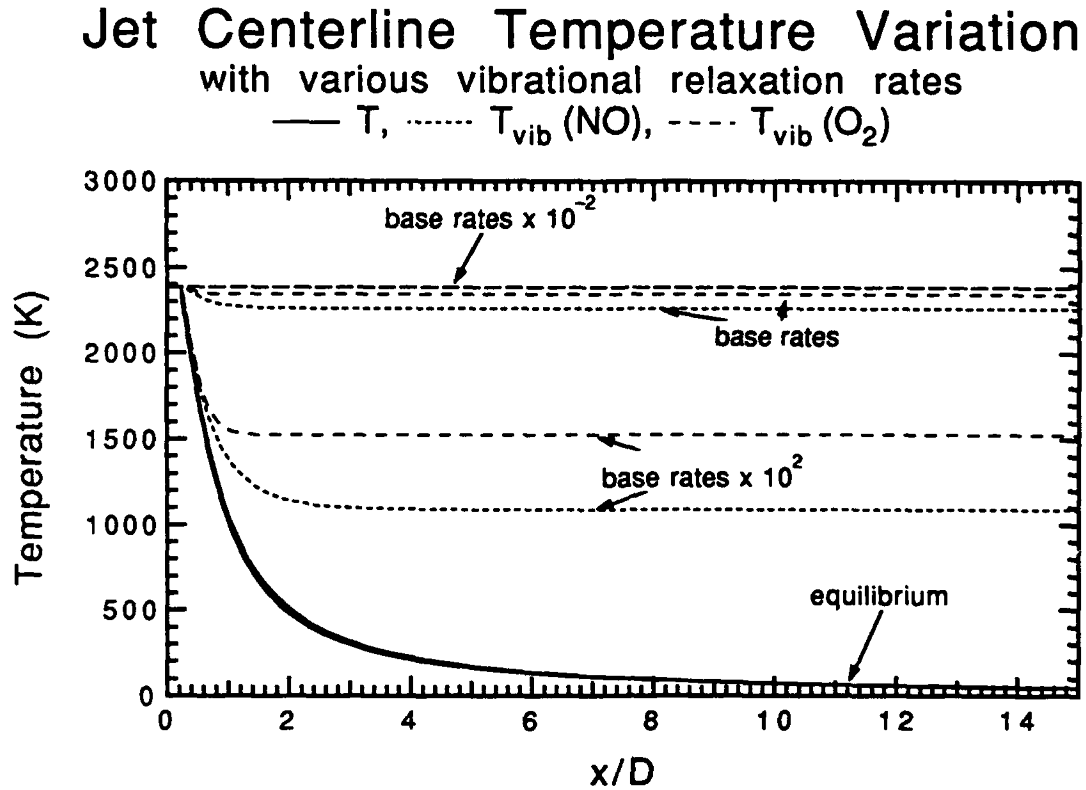


Fig. 6. Method-of-characteristics solutions for temperature on centerline of an underexpanded free jet with vibrational relaxation. Mixture is 2/77/21 of $NO/N_2/O_2$ with $D = 5$ mm, $T_s = 3200$ K, $P_s = 3.0$ atm.

4.2.2 PLIF Imaging of Shock Tunnel Flow

Nonequilibrium supersonic/hypersonic flows, relevant to current research on scramjets, pose new measurement problems for experimentalists. For example, experiments are often conducted in pulsed flow facilities in which the available measurement time is quite limited, thereby putting a premium on the ability to acquire complete data sets in very short times. In addition, many flows of interest exhibit a high degree of nonequilibrium, requiring experimental methods sensitive to such effects. PLIF has high potential for dealing with both of these critical problems, in that the data yield densities in specific quantum states of the species probed at a very large number of flowfield locations. During the past few years we have initiated research which addresses the primary problems inherent in extending PLIF to transient supersonic flows. Our strategy has been to employ a shock tube to provide the transient, high-enthalpy, supersonic flows of interest, and these experiments are now yielding important results. Specific accomplishments of the past year, discussed below, include the first applications of PLIF to a shock tunnel flow. Shock tube experimentation with transverse jet injection into a supersonic cross-flow is reported separately in Sec. 4.2.3.

Our shock tunnel experiments have been carried out in a standard pressure-driven shock tube, modified to include an exit nozzle in the shock tube end wall which separates the main body of the shock tube and a dump tank. A schematic of the experimental facility including associated optical and electronic components for PLIF imaging is shown in Fig. 7. This facility provides a convenient, economical and highly reproducible means of generating high-enthalpy, underexpanded free jets for a wide range of gas mixtures, jet expansion ratios and stagnation enthalpies. A schematic of a high-pressure ratio free jet was shown previously in Fig. 5 with the primary flow features labelled. This flowfield exhibits extreme variations in pressure and temperature, as well as high speed and Mach numbers, which render it a challenging and appropriate environment in which to explore and validate PLIF measurement strategies.

Experimental Facility

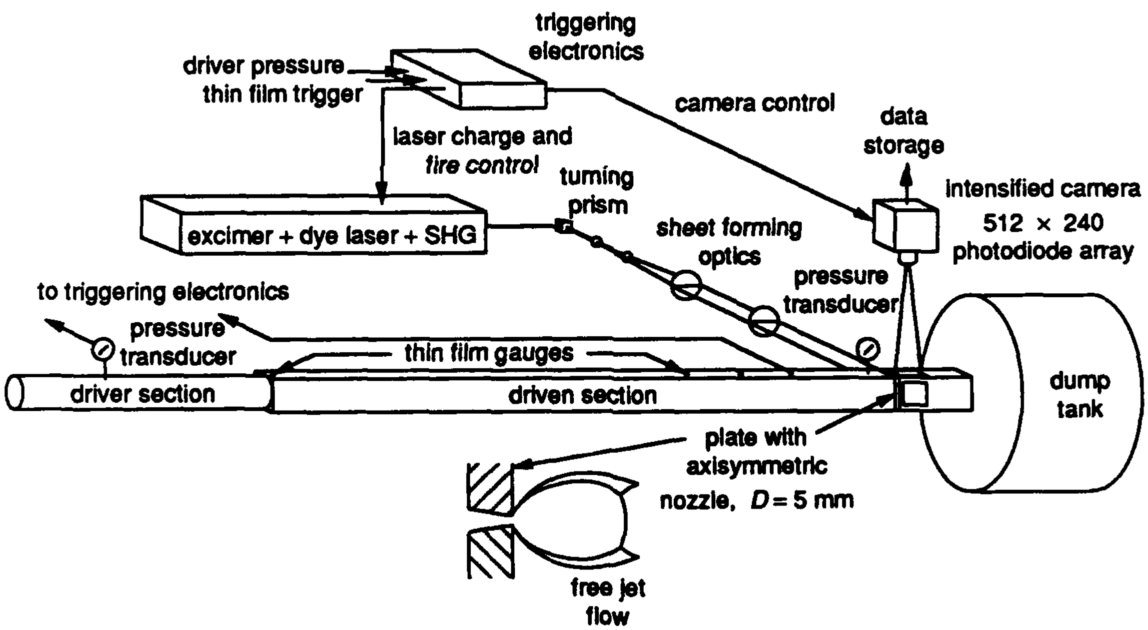


Fig. 7. Schematic of experimental facility with associated optical and electronic components for PLIF imaging in a shock tunnel.

Most of the research during the past year has focussed on the development of measurement strategies for rotational/translational temperature and velocity. The emphasis has been on NO, since it is generated in many practical high-enthalpy tunnels and, as a stable compound, can be conveniently seeded for use in low temperature flows. Although we have recently completed a thorough spectroscopic analysis of the NO spectrum in the A←X system, including development of a detailed fluorescence model which predicts the possible effects of rotational energy transfer and saturation phenomena, that work is now being prepared for publication and will not be detailed here. Rather we will highlight the experimental portion of the effort, which includes single-shot PLIF imaging of velocity and temperature, and the agreement found between these data and calculations carried out with our MOC code.

The temperature imaging was based on the ratio of fluorescence signals using laser pumping of different rotational states in the v = 0 vibrational level of the ground electronic state of NO. Owing to the wide temperature variation along the jet centerline, no two rotational states provide sensitive temperature determinations over the full extent of the jet. In order to study the influence of the state selected for pumping, we utilized 6 separate absorption transitions with rotational quantum numbers as low as 5 and as high as 28. As expected, the low rotational states provide the strongest signals and best temperature sensitivity in the lower temperature (highest Mach number) region of the jet, just upstream of the Mach disc, while the high rotational states provide the best signals nearer the nozzle exit where temperature is high. The best compromise choice for temperature determination was found to be: the $Q_1 + P_{21}(5)$ and $Q_2 + R_{12}(7)$ transitions (here the splitting of the main Q-branch and satellite transitions is small enough that the lines overlap almost fully and are treated as a single absorption line). Example results showing the temperatures inferred from single-shot and 5-frame-averaged data are given in Fig. 8. The stagnation conditions for this case are: 4200K, 3.0 atm, NO/Ar = 2/98. Even at these relatively low levels of NO, the single-shot signal-to-noise ratio is reasonably good, allowing good resolution of temperature. Note also that the agreement between the MOC code and the data is quite good. Our conclusion from this work is that PLIF imaging of NO in supersonic nonequilibrium flows holds high promise for applications in larger scale facilities used for various forms of propulsion research. Further work in our group will be aimed at refining the technique and extending it to include the vibrational temperature (which may differ from the rotational/translational temperature). Details of this work may be found in the recent AIAA (Reno, Jan. 1992) paper by Palmer et al. listed in Section 6.0.

Initial results have also been obtained for velocity using the Doppler-shift concept developed earlier in this laboratory. Data for velocity are acquired by slightly detuning the laser so that the central frequency of the laser line is nonresonant with the absorption line. In this case, the effective laser intensity depends on the local gas velocity component in the direction of illumination. Thus far, data have been limited primarily to purely radial illumination (i.e., at 90 degrees to the flow axis, the same as used for temperature imaging). Example single-shot data and a comparison with MOC calculations are shown in Fig. 8. The flow conditions are the same as noted above for the temperature data. The data have been interpreted using two different algorithms: a simple, linear fit to the laser lineshape; and a

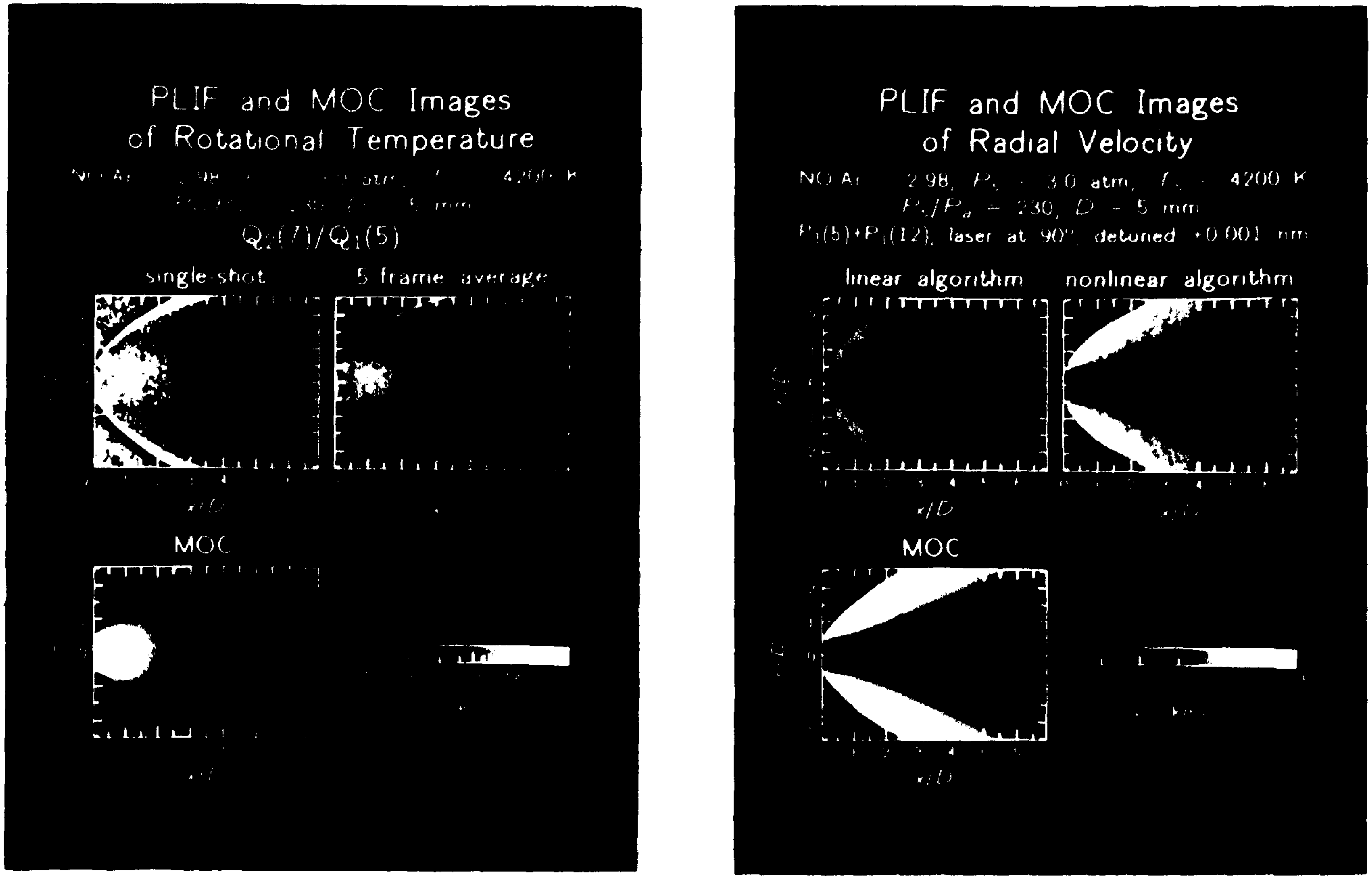


Fig. 8. PLIF imaging results and MOC calculations for a nonequilibrium supersonic free jet; the conditions for the experiment are indicated on the figure.

more complex, nonlinear fit. For large velocities, above about 600 m/s, it is clear that the nonlinear fit is required. The good agreement between the data and MOC calculation is very encouraging, especially in view of the fact that the data are acquired in a single laser shot.

We have carried out an analysis of the velocity imaging strategy and identified the aspects of the measurement which most need refinement. In particular, we conclude that key parameters of the laser should be monitored on each shot, particularly the laser energy, spatial distribution (i.e., the "sheet correction"), and the spectral distribution. At present, we seek conditions such that these variables are nearly constant from shot-to-shot, but further improvement in measurement accuracy will require greater attention to laser monitoring. Thus we are currently working to build the necessary monitoring apparatus, at which point we will return to the laboratory and attempt to characterize the measurement accuracy of the velocity determinations. We are also modifying the optical access to the free jet to allow axial as well as radial velocity measurements.

This project, as well as the MOC code described in Sec. 4.2.1, represents the Ph.D thesis research of Jennifer Palmer.

4.2.3 PLIF Imaging of Supersonic Jet Mixing and Combustion

During the past year we have continued our activity to develop PLIF strategies for imaging transverse jet mixing and combustion in supersonic cross-flow. This flow, illustrated in Fig. 9, is of generic interest to the problem of fuel mixing in scramjets. Our approach has been to use a shock tube to produce the supersonic stream, and a pulsed valve to generate the jet flow. This facility thus provides an economical and versatile test bed for research on diagnostics and on the fundamental properties of these flows.

Nonreactive jet mixing has been studied using imaging of NO, which can be seeded purely into the jet (usually with N_2 as the carrier gas), purely into the main shock tube flow, or into both regions. Each approach has merit in characterizing different aspects of the flowfield. Results reported thus far (see the AIAA papers and the submission to the Journal of Propulsion and Power by Lee et al. listed in Sec. 6.0) have been aimed at measuring the jet mixture fraction in single-shot images acquired in either an axial plane or transverse plane of the flow. Most recently, we have focussed on methods for single-shot imaging of temperature in such flows. The proposed strategy utilizes two lasers, each tuned to a separate line of NO, and two intensified CCD cameras to yield true "single-shot" temperature. Thus far we have solved numerous practical problems associated with establishing proper alignment between the cameras, proper synchronization of the two laser pulses, intensified camera gates, and computer acquisition of the two images. In addition, we have successfully overhauled the grating drive on one of the dye lasers to enable more precise wavelength tuning of the laser to the center of the absorption line of interest, and we have built an apparatus to monitor the spectral output of the laser on a single-shot basis. Finally, we have completed a thorough study of laser saturation effects in NO in order to establish the optimum laser excitation energy for linear-excitation PLIF imaging. We anticipate that the next series of tests to characterize the performance of the temperature imaging system will occur within the next two months.

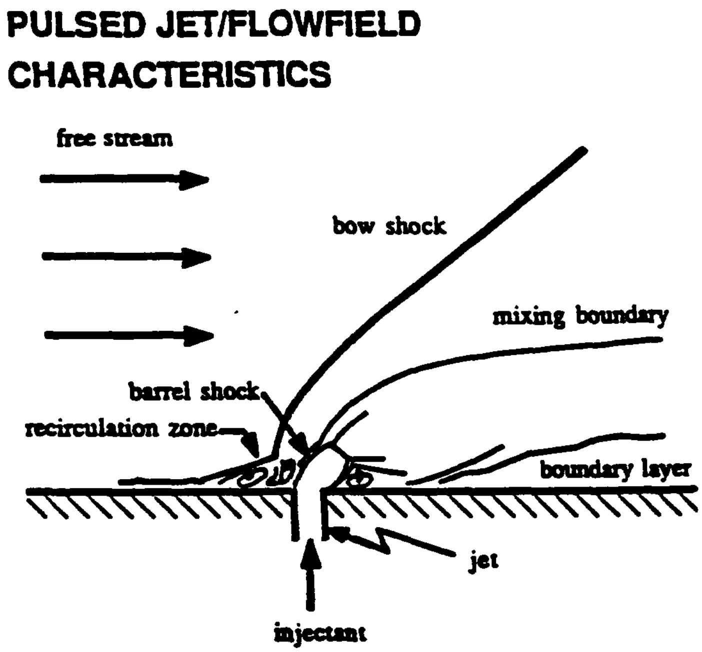


Fig. 9. **Schematic of the transverse jet flowfield, illustrating the characteristic flow features.**

In parallel with the work described above on nonreactive jets, we have also continued research with reacting jets. The fuel is H_2, seeded with a trace of NO in some cases, and the shock tube gas is a mixture of O_2/N_2 simulating air; the "air" can also be seeded with trace levels of NO when required. The primary observable in past work has been PLIF imaging of OH; this serves as a convenient marker of the instantaneous reaction zone in the combusting mixture. High quality, single-shot PLIF images have been acquired over a range of flow and jet conditions, and for both transverse and axial plane illumination. The important observations made in these tests are: (1) the appearance of large-scale structures in the reaction zone; and (2) the significant level of burning observed in the side wall boundary layer. At present we are modifying the test section to incorporate a backward facing step and to improve the plumbing of the pulsed valve to give more constant stagnation pressures during the duration of the pulsed jet.

In future work with the combusting jet, we plan to augment the measurements to include: (1) PLIF images of temperature, using both OH and NO; in the latter case we will require NO seeded at low levels in both the fuel stream and in the shock tube gases; (2) PLIF images of OH to reveal the flame front and boundary layer combustion; and (3) PLIF images of fuel mixture fraction, tentatively through judicious seeding of NO in both the fuel and shock tube gases. These quantities will be interpreted in terms of the relevant flow parameters, such as step height and distance between step and fuel nozzle, and also as a function of the jet and mainstream momentum flux ratio. In these planned tests, our most current capability for monitoring laser sheet uniformity, laser pulse energy, and laser spectral distribution will be utilized. We hope to complete this series of tests this summer, at which point the current graduate student, Mr. Brian McMillin, will have completed his Ph.D research.

4.3 Future Work

During the next year, we plan to continue some of the activities described above and initiate related work. This work will include:

- Research on PLIF imaging of temperature and velocity in shock-heated supersonic free jets with vibrational and chemical nonequilibrium
- Research on PLIF imaging diagnostics for application in transverse nonreacting and reacting jets in supersonic cross-flow.
- Application of selected PLIF imaging techniques in the Stanford supersonic mixing layer facility; this will include imaging of OH in H_2-air flows as well as imaging of tracers to give mixing and temperature information.

5.0 NUMERICAL SIMULATIONS

5.1 Objective and Previous Results

The objective of this phase of the program is to use direct numerical simulations (DNS) to gain insight into the dynamics of mixing and heat release in subsonic and supersonic mixing layers. A fundamental understanding of the coupling between heat release and fluid dynamics in simple flows is a necessary step towards understanding more complex flows.

5.2 Status of the Research

Our linear stability analysis results, reported previously, revealed the following:

- The reacting mixing layer behaves as two independent colayers during its early development.
- The 'flame convective Mach numbers,' which we introduced for the two colayers (Planche and Reynolds, 1991a), are the preferable parameters for correlating compressibility effects in reacting mixing layers.
- At low convective Mach numbers heat release reduces the growth rate and the amount of product formed, but at high Mach numbers heat release increases the growth rate of the layer.

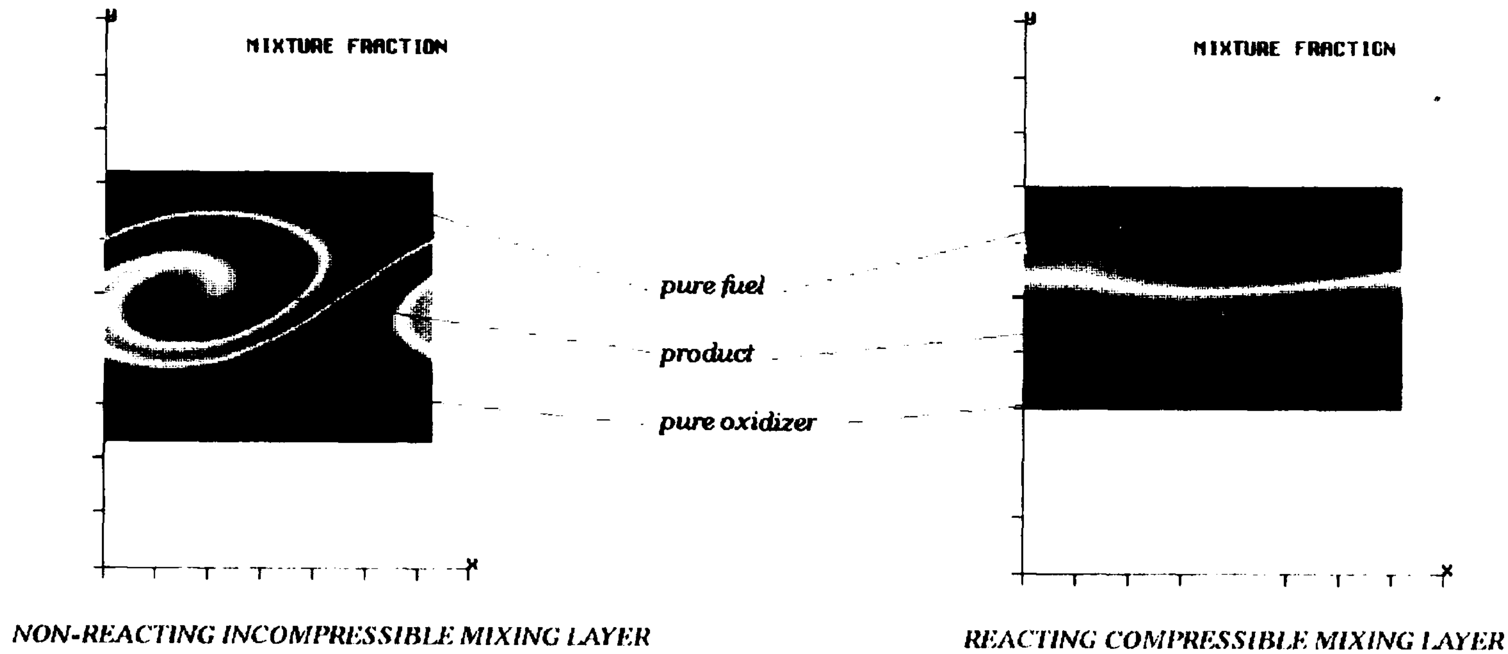
Subsequent 2-D DNS confirmed the results at the linear stability analysis and additionally revealed the following:

- The fast and slow outer modes do not interact (Fig. 10).
- A mixing model based on large-scale engulfment of fluid from both sides of the mixing layer may not be appropriate in compressible reacting mixing layers.

Our main objective during the past year was to address the following questions:

- Does vortex pairing occur in the reacting supersonic mixing layer? If not, what is the mechanism for mixing-layer growth?
- Does heat release cause the large structures of the reacting mixing layer to remain two-dimensional at high Mach numbers?

Related issues of interest are the mechanism for the transition to turbulence and the influence of streamwise vortices on mixing and reaction.



D.N.S. of supersonic reacting mixing layers

Fig. 10. **Comparison of the structure of the incompressible non-reacting mixing layer (left) with the structure of the compressible reacting mixing layer (right). Note the existence of two zones of mixing in the compressible reacting case.**

5.2.1 Mixing Layer Growth Mechanism

Simulations show that the growth mechanism in a compressible reacting mixing layer (CRML) is different than in an incompressible uniform density mixing layer (IUDML). The IUDML grows by vortex pairing. In the CRML the vortices in each colayer grow, saturate and then decay, transferring energy back to the mean flow (Fig. 11). It was shown that the transfer of energy back to the mean flow is due to the modification of the mean angular momentum r dU/dy, as the hot fluid is carried away from the central reaction zone by the colayer eddies (Planche and Reynolds, 1992).

We have not observed vortex pairing in the CRML. Instead, under certain conditions one larger structure can swallow a neighboring smaller structure on the same side of the layer ("gulping"), as illustrated in Fig. 12. We believe that the absence of pairing is due to the different phase speeds of the structures on the two sides of the flame sheet.

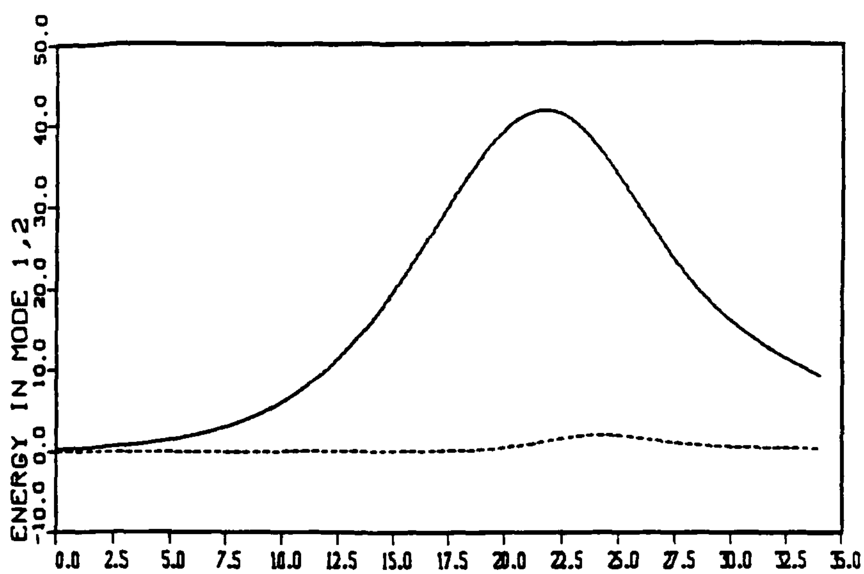


Fig. 11. Time variation of the kinetic energy of a typical outer mode.

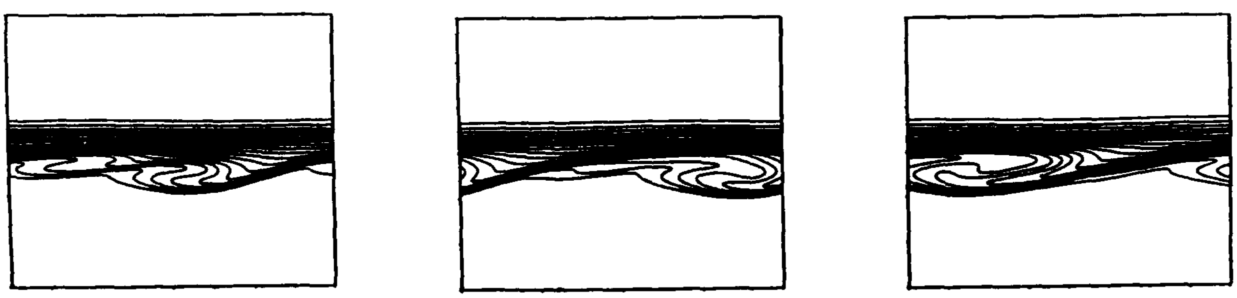


Fig. 12. Mixture fraction contour of the compressible reacting mixing layer during the interaction of a slow outer mode and its subharmonic ("Gulping").

5.2.2 Transition to Turbulence

Results from the 3-D time dependent turbulence simulation suggest a mechanism for the transition to turbulence. The transition initially preserves the two colayers and strongly increases the total reaction rate. Our principal observations are summarized below:

Before the transition:

- Among all the eigenmodes used to initialize the simulation, the 2-D modes are initially fastest growing, as shown in Fig. 13.

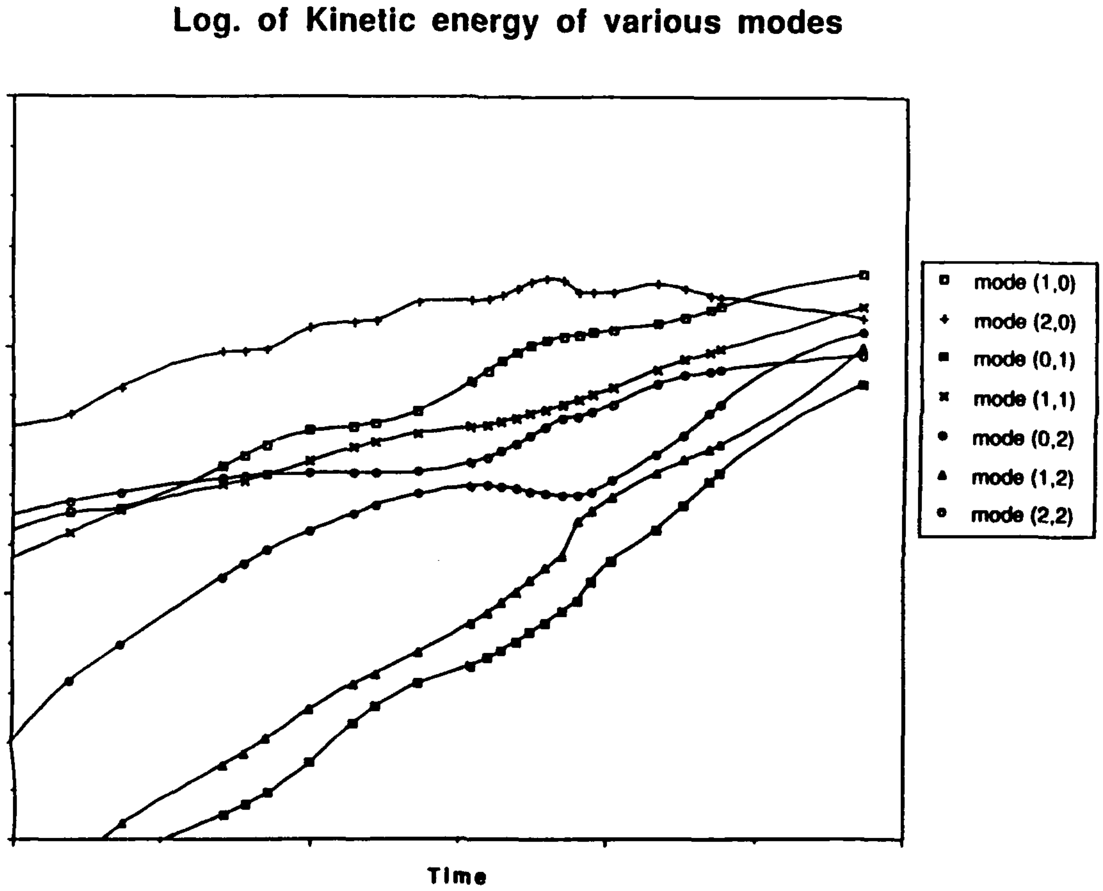


Fig. 13. Time variation of the kinetic energy of various instability modes in a 3-D simulation. Initially only 2-D modes ((1,0) and (2,0)) and 45 deg. modes ((1,1) and (2,2)) are present. The 2-D modes are initially dominant, but the streamwise vortices are the fastest growing modes.

- The flow appears dominated by four strong spanwise vortices, two on each side of the layer. The top view of the high vorticity region shows the two non-interacting colayers (Fig. 14).

80% of the maximum spanwise
vorticity surface at t=20 and t=40
(Top view- flow from left to right)

Fig. 14. **High vorticity regions of the compressible reacting mixing layer before the transition (left) and during the transition (right). Initially the flow is dominated by four large-scale vortices (two on each side of the layer). Note the existence of hairpin vortices during the transition.**

- The eddies in the two colayers travel at different speeds, preventing interaction between eddies on opposite sides of the flame sheet.
- The structure of the layer is constantly changing with time, suggesting that large eddies, even if present, will be difficult to identify in experiments.

Transition:

- The transition to turbulence is caused by the rapid growth of streamwise vortices. The interaction of growing 2-D modes and growing 45 degree modes generates streamwise modes (Craik-type resonances).
- The transition is similar to what is observed for incompressible wall boundary layers (Fig. 15). Initially, the central region of the 2-D vortex is pushed upward by streamwise vortices. The portion of the vortex pushed upward is entrained by fluid moving faster than the fluid surrounding the remaining part of the vortex. This process leads to the stretching and breaking of the spanwise vortex and generates intense x and y vorticity.
- The transition to turbulence occurs in the absence of pairing of spanwise vortices.

MECHANISM OF THE TRANSITION TO TURBULENCE

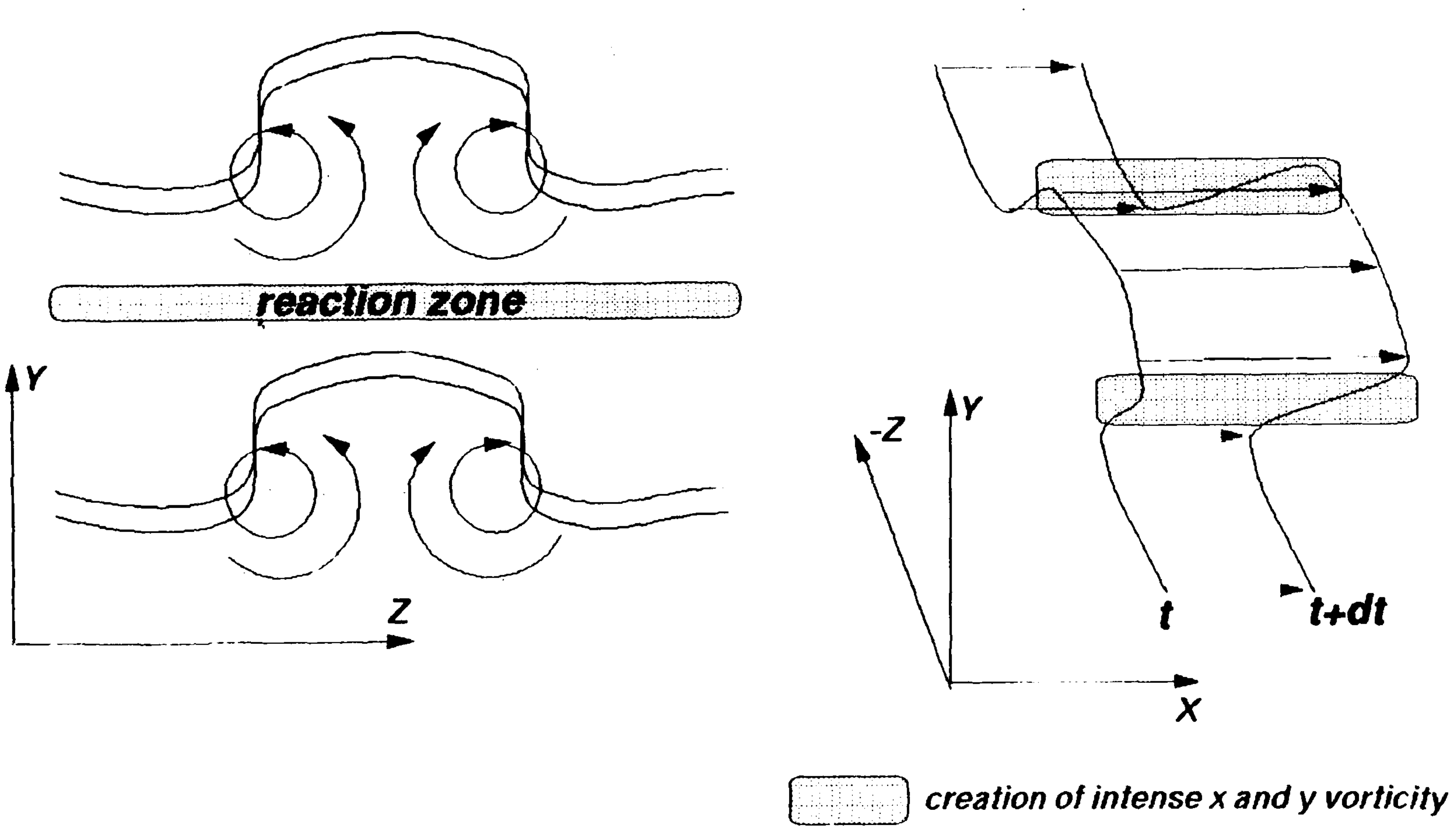


Fig. 15. Proposed mechanism of transition. The transition is similar to what is observed in wall boundary layers. It occurs on both sides of the layer and therefore preserves the two colayers.

- The transition occurs on both sides of the layer and initially preserves the two colayers.

These results suggest that after an initial linear stage characterized by 2-D fast and slow vortices the CRML evolves into a fully turbulent flow with strong streamwise vortices (Fig. 15). The use of streamwise vortex generators to enhance the reaction rate is therefore suggested.

5.3 Future Work

Future work will focus on the following extensions:

- Investigation of the optimal location of streamwise vortices to enhance reaction and mixing in the CRML using 3-D temporal simulations on the Hypercube.

- Study of the influence on the ignition delay on the amount of mixing occurring before reaction, and on the downstream evolution of the layer using 2-D spatial simulations on Cray YMP.

6.0 PRESENTATIONS AND PUBLICATIONS

6.1 Presentations (2/91 - 2/92)

B. K. McMillin, M. P. Lee, J. L. Palmer and R. K. Hanson, "Two-Dimensional Temperature Measurements of Nonequilibrium Supersonic Flows Using Planar Laser-Induced Fluorescence of Nitric Oxide," paper AIAA-91-1670 at AIAA 22nd Fluid Dynamics, Plasma Dynamics and Lasers Conference, Honolulu, Hawaii, June 24-26, 1991.

J. L. Palmer, B. K. McMillin and R. K. Hanson, "Planar Laser-Induced Fluorescence Imaging of Underexpanded Free Jet Flow in a Shock Tunnel Facility," paper AIAA-91-1687 at AIAA 22nd Fluid Dynamics, Plasma Dynamics and Lasers Conference, Honolulu, Hawaii, June 24-26, 1991.

B. K. McMillin, M. P. Lee, J. L. Palmer and R. K. Hanson, "Two-Dimensional Imaging of Shock Tube Flows Using Planar Laser-Induced Fluorescence," presented at 18th International Symposium on Shock Waves, Sendai, Japan, July 1991.

N. T. Clemens, P. H. Paul, M. G. Mungal, and R. K. Hanson (1991), "Scalar mixing in the supersonic shear layer", AIAA-91-1720, AIAA 21st Fluid Dynamics, Plasma Dynamics & Lasers Conference, Honolulu, HI.

O. H. Planche and W. C. Reynolds (1991) "Compressibility Effects on the Supersonic Reacting Mixing Layers," AIAA-91-0739.

O. H. Planche and W. C. Reynolds (1991) "Direct simulation of a supersonic Reacting Mixing-Layer," Eighth Symposium on Turbulent Shear Flows, paper 21-1.

J. L. Palmer, B. K. McMillin and R. K. Hanson, "Planar Laser-Induced Fluorescence Imaging of Velocity and Temperature in Shock Tunnel Flows," paper AIAA 92-0762, AIAA 30th Aerospace Sciences Meeting, Reno, Jan. 1992.

B. K. McMillin, J. L. Palmer and R. K. Hanson, "Instantaneous 2-D Temperature Measurements of Shock Tube Flows using Laser-Induced Fluorescence of Nitric Oxide," to be presented at Measurement Technology Conf., NASA Langley Res. Ctr., April 22-23, 1992; paper to appear in Symposium Proceedings.

B. K. McMillin, J. L. Palmer and R. K. Hanson, "Instantaneous 2-D Temperature Measurements of a Transverse Jet in a Shock-Heated Supersonic Crossflow," paper to be presented at 20th AIAA/SAE/ASME/ASAE Joint Propulsion Conference, Nashville, July 6-8, 1992.

O. H. Planche and W. C. Reynolds (1992) "Heat Release Effects on Mixing in Supersonic Reacting Mixing Layers," AIAA-92-0092.

6.2 Publications (2/91 - 2/92)

M. P. Lee, B. K. McMillin, J. L. Palmer and R. K. Hanson, "Two-Dimensional Imaging of Mixing and Combustion of Transverse Jets in Shock Tube Flows," J. Prop. and Power, in press.

B. K. McMillin, M. P. Lee, P. H. Paul and R. K. Hanson, "Planar Laser-Induced Fluorescence Imaging of Shock-Induced Ignition," *Twenty-Third Symposium (International) on Combustion*, The Combustion Institute, 1909-1913 (1990).

M. G. Mungal, and N. T. Clemens (1991), "Side-Wall Shock Vortex Generator (SWSVG) for Supersonic Mixing Enhancement", Bull. Amer. Phys. Soc., 36(10), 2615.

N. T. Clemens and M. G. Mungal (1991), "A planar Mie scattering technique for visualizing supersonic mixing flows", Expts. Fluids, 11, 175-185.

N. T. Clemens and M. G. Mungal (1992a), "Two- and three-dimensional effects in the supersonic mixing layer", to appear AIAA J.

N. T. Clemens and M. G. Mungal (1992b), "Effects of side-wall disturbances on the supersonic mixing layer", J. Prop. Power, 8(1), 249-251.

7.0 PERSONNEL

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8.0 Ph.D. DEGREES AWARDED

Noel Clemens, June 1991, "An Experimental Investigation of Scalar Mixing in Supersonic Turbulent Shear Layers."

Michael Lee, November 1991, "Temperature Measurements in Gases Using Planar Laser-Induced Fluorescence Imaging of NO and O_2."